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Abstract. This paper describes the Outdoor Accelerated-weathering Tracking System (OATS) and interim results for the first OATS study on photovoltaic (PV) modules. With two test planes measuring 1.52 x 1.83 m, OATS provides a unique solar-concentrating exposure capability. Test sample temperatures are moderated by air blowers. Water spray capability exists for wetting samples. The OATS two-axis tracker points to the sun using software calculations. Non-imaging aluminum reflectors give a nominal clear-sky optical concentration ratio of three. Field-qualification measurements in the test plane under reflector conditions showed its relative irradiance non-uniformity was " 15% for a clear-sky summer day with " 75 mm as the smallest distance for that non-uniformity. Exposure studies began in November 1997 on seven pairs of commercially available ribbon silicon, crystalline silicon and amorphous silicon PV modules kept at constant resistive load. The modules were periodically removed from OATS for visual inspection and solar simulator performance measurements. There were no module failures. This PV module study is ongoing and later results will be compared to other testing techniques. Through July 1998, the modules under reflector conditions received 392 MJ/m^2 of total ultraviolet (TUV) exposure. That was 2.07 times the TUV exposure compared to a south-facing fixed array tilted 40° up from horizontal at NREL. Similarly, the modules in the test plane under the covered reflectors received 1.04 times the fixed array TUV exposure. For the test plane under the covered reflectors there was a loss of 13% TUV exposure attributed to the reflectors blocking some of the diffuse-sky UV light. Also through July 1998, the OATS sunlight availability measured 95% compared to the cumulative global normal exposure at the NREL Solar Radiation Research Laboratory (SRRL). The OATS sunlight availability losses included downtime when the PV modules were removed, and when there were OATS tracking problems, maintenance, and repair. For December 1997 through July 1998, the SRRL cumulative exposure was 99% compared to the respective monthly averages from years 1961 through 1990 at Boulder, Colorado.

INTRODUCTION

The Outdoor Accelerated-weathering Tracking System (OATS) was procured by NREL through a competitive proposal process. The OATS is a unique sunlight-concentrating design based largely on Carizzo Solar Plains tracker technology. The OATS system is meant to provide accelerated stress testing of photovoltaic (PV) modules. The testing purpose is to assess the ability of a module to withstand ultraviolet (UV) radiation and outdoor exposure, focusing on degradation of module encapsulants and other polymer components, the PV device structures, and general module components. The first PV modules were deployed 11/22/97. This paper describes OATS and provides interim results because there are not yet test failures.

SYSTEM DESCRIPTION

The OATS is a two-axis solar tracking weatherometer having two test planes 1.52 m (5 ft) by 1.83 m (6 ft) that can accomodate 206 kg (500 lbs) each. The test planes have air blowers for ambient air cooling of samples and water spray nozzles for wetting samples. A manually programmable timer controls the air blowers and nozzles. The solar tracking is by time and relative position encoders on azimuth and elevation electric motors. Software calculates the sun position and signals the control electronics to step the motors. Because tracking is not by open feedback from monitoring sunlight, clouds do not affect the pointing and off-axis tracking may be prescribed. The OATS system automatically stows when a wind overspeed condition is sensed.

Solar concentration is by four flat rectangular aluminum reflector panels giving nominal one- two- or three-times direct-beam concentration by covering opposing pairs of reflectors. The aluminum reflector material total solar-weighted specular reflectance measured 88%. The reflectance is 83% to 92% in the UV range for wavelengths < 400 nm, 79% to 93% in the 400-to-750 nm range, and is primarily in the mid-90% range beyond that out to 2400 nm. Field-qualification measurements in the test plane under reflector conditions using a 50-by-100 mm crystal silicon device showed the OATS test plane relative irradiance non-uniformity was " 15% for a clear-sky summer day. And using an 8-mm-diameter crystal silicon device, " 75 mm was found to be the smallest distance for the " 15% non-uniformity.

The computer-based data acquisition system (DAS) for OATS monitors irradiance, environmental, and test sample parameters. The DAS was designed at NREL using commercially available components. The design allows a wide choice of user-specified transducers. The DAS works under user-written software for in-situ, continuous or conditional data sampling. The DAS hardware is composed of a data logger, two multiplexers, a controller switching 12 three-pole relays, and a coaxial-cable interface to a personal computer in the NREL Outdoor Test Facility (OTF) 40 m (125 ft) away from OATS.

The DAS is programmed to take data measurements every 5 seconds with averages recorded either at 5-m or 15-m intervals. Sample monitoring has 16 thermocouple and 32 differential voltage channels. Those data are averaged over 15-m intervals during sunshine. Three sets of environmental and irradiance data are reported over 5-m and 15-m intervals during sunshine, and at 15-m intervals otherwise. Daily cumulative irradiance values are also recorded. Irradiance measurements taken outside the test planes are the total irradiance-tracking (Kipp & Zonen pyranometer), total ultraviolet (TUV) irradiance-tracking, (Eppley Lab TUVR pyranometer with passband limits at 295 to 385 nm), normal incidence irradiance-tracking (Eppley Lab pyrheliometer) and, total irradiance-tracking (using a crystal silicon solar cell device called an ESTI sensor). The ESTI sensor includes a temperature sensor to allow temperature correction to its irradiance measurement. The environmental and irradiance measurements in each test plane are the total irradiance, total ultraviolet irradiance, ambient temperature, relative humidity and surface wetness.

EXPERIMENT PLAN

Test protocol for OATS was based on existing standards (1, 2). It was decided not to use water spray cycles until baseline experience is established. This first study will ultimately compare OATS results at solar-concentrating conditions and at non-concentrating conditions to other exposure testing techniquesCto sunlight exposure on outdoor fixed racks and to lamp exposure in environmental chambers.

Seven pairs of commercially available ribbon silicon, crystalline silicon, and amorphous silicon (a-Si) PV modules (Table 1) were procured and one of each was deployed in the two OATS test planes. One test plane had its reflectors covered so the irradiance is nominally equal to that seen by a two-axis tracker. Each PV module was put at a resistive load calculated to provide approximate one-sun maximum power-point operation. In-situ monitoring is back of module temperature by a copper constantan thermocouple and load current to a shunt resistor. Load voltage may also be monitored. Once a day, module short-circuit current and open-circuit voltage are measured when OATS total irradiance-tracking is near 1000 W/m^2. The OATS air blowers were planned to be used to keep the module temperature no greater than 15C above what is estimated to be the maximum normal operating cell temperature (60C65C) for modules at one-sun conditions.

TABLE 1. OATS Test Photovoltaic Module Descriptions

Manufacturer	**Module Models**	**Technology**
Applied Power Corp.	APC50	ribbon silicon
Siemens Solar Industries	M10 & Pro 1JF	crystalline silicon
Solarex Corp.	MSX10 & MSX20	crystalline silicon
United Solar Systems Corp.	UniSolar 1206 & 1212	Dual-junction amorphous silicon

This OATS exposure study was planned to be done in intervals up to 2000 MJ/m^2 TUV exposure or until failure defined as module power having decreased to 25% of its initial value. The TUV test dose exposure is defined as the UV irradiance integrated below 400 nm. The first TUV exposure interval was planned at 54 MJ/m^2. Subsequent TUV intervals should be every 100MJ/m^2 or so, until failure. At the intervals the PV modules are removed from OATS for visual inspection and solar simulator performance measurements. When modules pass the rated power criteria they are returned to OATS for continued exposure testing; otherwise they undergo failure analysis.

RESULTS

There have been no PV module failures. Interim results and comments follow. The air blowers have been used during the day starting in March 1998 and ongoing, for both test planes. The reported TUV levels include a 1.26 multiplier applied to the measured data. That is because the TUV test dose was defined as integrated below 400 nm, and because the TUVR instrument spectral response ends at 385 nm. Measurements at SRRL were used to establish the TUVR multiplier to account for the 385C400-nm range (3).

Modules were periodically removed from OATS and visual inspection and solar simulator current-voltage (I-V) measurements were made. Visual inspections showed some minor anomalies, however no modules exhibited any serious defects. Modules #1.2 to #7 were under reflector conditions, and modules #9.2 to #15 were in the test plane with the reflectors covered.

The I-V performance data were reviewed and compared to the baseline measured in March 1997 (Table 2). So far, only the amorphous silicon modules showed any substantial change and that is attributed to the Staebler-Wronski effect. Some modules also had dark I-V measurements made. The dark I-V provides estimates for the PV module series and shunt resistance values, and for the equivalent series resistance value. By considering the changes in those resistance values along with the changes in the shape of the light I-V curves, and along with visual inspection findings, it is possible to provide hypotheses for module performance losses. For example, a loss in short-circuit current without significant change in I-V slopes or resistances might lead to hypothesizing the loss is due to darkening of the encapsulant or superstrate.

The OATS irradiance exposure levels for December 1997 through July 1998 were compared to some benchmarks. The PV modules under reflector conditions received 392 MJ/m^2 of TUV exposure, that being 2.07 times the value on a south-facing fixed array

TABLE 2. Photovoltaic Module[a] Relative Power After OATS Exposure [b]

Module Model - #		Relative Power (% @ standard reporting conditions)				
APC50	#1.2	100	96.4	95.5	-----	-----
APC50	#9.2	100	97.7	96.7	96.6	-----
M10	#2	98.2	96.3	97.6	98.0	95.8
M10	#10	98.2	98.3	98.9	97.5	-----
Pro1JF	#3	97.2	95.9	96.2	97.0	95.7
Pro1JF	#11	97.3	96.1	94.9	94.8	-----
MSX10	#4	99.2	98.2	98.5	98.7	97.6
MSX 10	#12	98.5	97.7	97.2	97.1	-----
MSX20	#5	99.2	97.3	98.3	98.8	97.1
MSX20	#13	98.7	98.2	98.1	99.8	-----
1206	#6	85.6	77.8	71.7	71.0	72.8
1206	#14	84.3	67.1	64.7	65.7	
1212	#7	86.1	80.0	74.2	74.6	74.3
1212	#15	89.2	71.4	68.2	68.9	-----

(a) Modules #1.2 - #7 @ OATS reflector conditions. Module power % is relative to 3/97 measurement except #1.2 and #9.2 relative to 11/97 measurement since they weren't measured 3/97. All modules were exposed (1-sun outdoors) about 30 days during 3/97 to 11/97.

(b) TUV Exposure levels MJ/m2 (date) for modules #1.2 and #2 - #7 and #9.2 - #15 follow.

#1.2	0 (3/98)	95 (5/98)	228 (7/98)	-----	-----
#2 - #7	0 (11/97)	54 (1/98)	165 (3/98)	260 (5/98)	392 (7/98)
#9.2 - #15	0 (11/97)	54 (2/98)	158 (5/98)	240 (8/98)	-----

tilted 40° up from horizontal at NREL (4). Similarly, the modules in the test plane under the covered reflectors received 197 MJ/m^2, that being 1.04 times the fixed array value. That OATS test plane experienced 13% TUV loss compared to the OATS value measured

outside the test planes. The loss is attributed to the reflectors blocking some of the diffuse-sky UV light. Overall, the OATS sunlight availability was 95% compared to the cumulative global normal exposure at SRRL (5). The OATS availability losses included time the modules were removed from exposure and downtime for OATS problems, maintenance, and service for upgrading the tracker control electronics. The SRRL cumulative average exposure was 99% compared to the respective monthly averages for years 1961 through 1990 at Boulder, Colorado (6).

This initial PV module study will continue. The OATS test protocol is new and will be adjusted as more experience is gained. In-situ data will be more closely reviewed. Hardware upgrade modifications are planned for the sample monitoring, especially for the back of module temperature. And, the OATS results will be compared to other exposure methods when failures or substantial visual anomalies are noted.

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